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齿轮结构参数和误差对某动力装置主齿轮传动振动的影响

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摘　要: 建立单级斜齿轮传动振动模型, 然后建立某动力装置主齿轮传动振动的动力学模型, 应用模态分析法对该模型进行求解, 分析讨论了结构参数和误差对主齿轮传动振动的影响, 并得到了相应的结论。

关　键　词: 齿轮传动; 振动

中图分类号: TH132.41　　文献标识码: A

1　引言

齿轮传动是船舶动力装置的主要组成部分, 其性能直接影响到动力装置的正常工作。船用主机转速高, 功率大, 常引起齿轮的失效。失效原因除强度问题外, 往往还由于齿轮振动过大。齿轮传动振动与噪声问题甚至影响到舰艇的战斗力与生命力。影响齿轮传动振动的因素主要包括: 齿轮结构参数和加工安装误差、负载、润滑条件、轴及轴承、箱体等。本文利用模态分析法, 研究了齿轮结构参数和加工安装误差等因素对某型动力装置主齿轮传动振动的影响, 并提出了相应的减振措施。

2　单级斜齿轮传动的振动微分方程

在弹性支承情况下, 作如下假设:

(1)斜齿圆柱齿轮传动所传递的扭矩恒定;

(2)轮齿为线弹性体。仅考虑法向变形, 不考虑轮齿的塑性变形、热变形和轮体的变形;

(3)除柔性扭力轴外其余轴均为刚性轴;

(4)轮齿啮合时沿理论接触线全部接触;

(5)仅考虑弯扭耦合振动。

基于以上假设, 单级斜齿轮传动振动微分方程为:

$$\ddot{x} + 2\zeta\sqrt{\frac{K}{M}}\dot{x} + \frac{K}{M}x = \frac{1}{M}(F_0 + F_e) \tag{1}$$

式中 x, $\dot{x}$, $\ddot{x}$ —— 沿啮合线方向的位移、速度和加速度; M —— 齿轮副等效质量;

$$M = \left(\frac{r_{b1}^2}{J_1} + \frac{r_{b2}^2}{J_2} + \frac{1}{M_1} + \frac{1}{M_2}\right)^{-1}$$

J_1、M_1、J_2、M_2 为主、从动齿轮对转轴的转动惯量和质量; r_{b1}、r_{b2} 为主、从动齿轮基圆半径; ζ—— 相对阻尼系数, $\zeta = 0.05 \sim 0.15$。大小取决于齿轮箱结构形式等; K —— 斜齿轮啮合刚度, $K = k(t, x)$; F_0—— 静态齿面作用力; F_e—— 附加齿面作用力, $F_e = \sum_{n=1}^{N} k_n e_n(t, x)$, k_n、$e_n(t, x)$ 分别为第 n 对啮合齿对的啮合刚度和瞬时综合误差, N 为啮合对数。

3　某型动力装置二级斜齿轮传动振动动力学模型

3.1　动力学模型

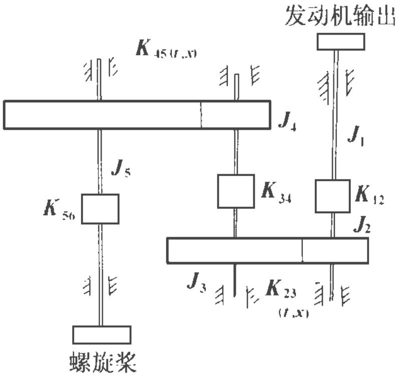

图 1　某型动力装置二级斜齿轮传动结构示意图

图中, J_1, J_2, J_3, J_4, J_5 为各轴的当量转动惯量; K_{12}, K_{34}, K_{56} 为各轴的扭转刚度; $K_{23}(t, x)$, $K_{45}(t, x)$ 分别为第一级和第二级齿轮副在瞬时 t 的啮合刚度; r_{b1}, r_{b2}, r_{b3}, r_{b4} 为各齿轮基圆半径。

利用前面的假设, 图 1 所示系统可化为图 2 示的系统振动动力学模型。

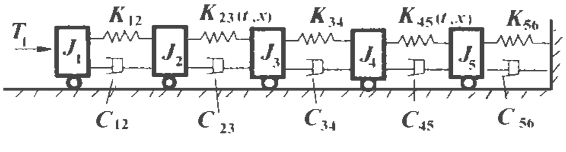

图 2　系统振动动力学模型

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该系统为多自由度振动系统, 其振动方程为

$$[J]\{\ddot{\theta}\}+[C]\{\mathring{\theta}\}+[K]\{\mathring{\theta}\}=\{T_\theta\} \qquad (1)$$

其中$\{\theta\}\{\ddot{\theta}\}\{\mathring{\theta}\}$ 为角位移列阵, 角速度列阵和角加速度列阵;

$\{T_\theta\}=\{[T_{\theta1}\,T_{\theta2}\,T_{\theta3}\,T_{\theta4}\,T_{\theta5}]^T\}$, $T_{\theta1}$ 为系统的输入扭矩;

$T_{\theta2}$, $T_{\theta3}$, $T_{\theta4}$, $T_{\theta5}$ 为激振力, 取决于齿轮参数及综合误差;

$[J][C][K]$ 分别为质量矩阵, 阻尼矩阵和刚度矩阵。表述如下:

$$[J]=\begin{bmatrix} J_1 & & & & \\ & J_2 & & 0 & \\ & & J_3 & & \\ & 0 & & J_4 & \\ & & & & J_5 \end{bmatrix}$$

$$[C]=\begin{bmatrix} c_{12} & -c_{12} & 0 & 0 & 0 \\ -c_{12} & c_{23}+c_{12}r_{b1}^2 & -c_{23}r_{b1}r_{b2} & 0 & 0 \\ & -c_{23}r_{b1}r_{b2} & c_{34}+c_{23}r_{b2}^2 & -c_{34} & 0 \\ 0 & 0 & -c_{34} & c_{45}+c_{34}r_{b3}^2 & -c_{45}r_{b3}r_{b4} \\ 0 & 0 & 0 & -c_{45}r_{b3}r_{b4} & c_{56}+c_{45}r_{b4}^2 \end{bmatrix}$$

$$[K]=\begin{bmatrix} k_{12} & -k_{12} & 0 & 0 & 0 \\ -k_{12} & k_{23}(t,x)+k_{12}r_{b1}^2 & -k_{23}(t,x)r_{b1}r_{b2} & 0 & 0 \\ 0 & -k_{23}(t,x)r_{b1}r_{b2} & k_{34}+k_{23}(t,x)r_{b2}^2 & -k_{34} & 0 \\ 0 & 0 & -k_{34} & k_{45}(t,x)+k_{34}r_{b3}^2 & -k_{45}(t,x)r_{b3}r_{b4} \\ 0 & 0 & 0 & -k_{45}(t,x)r_{b3}r_{b4} & k_{56}+k_{45}(t,x)r_{b4}^2 \end{bmatrix}$$

$K_{34}=\left(\frac{1}{K_T}+\frac{1}{K_G}\right)^{-1}$, $K_G=r^2K'_G$, $K_T=GJ_P/l$, K'_G 为齿轮联轴节啮合刚度, r 为其分度圆半径。J_P——轴的极惯性矩, k_T——轴的扭转刚度。

3.2 用模态分析法对方程进行解耦

采用模态分析法对式(1)进行解耦。首先将系统啮合刚度周期分为若干段, 使非线性微分方程组(1)变为分时段的常系数线性微分方程组。

令 $\tau=t/T$, 代入(1), 得:

$$[J_z]\{\ddot{\theta}\}+T[C]\{\mathring{\theta}\}+T^2[K]\{\ddot{\theta}\}=T^2\{T_\theta\} \qquad (2)$$

引入正刚坐标$\{\Phi_N\}=\{\theta_N\}^{-1}\{\theta\}$, $\{\theta\}=\{\theta_N\}\sin(\tilde{\omega}_n t+\varphi)$, 式(1)化为如下形式

$$\{\ddot{\Phi}_N\}+T[C_N]\{\dot{\Phi}_N\}+T^2[\Omega_n^2]\{\Phi_N\}=\tau^2\{T_{\theta N}\} \qquad (3)$$

式(3)中

$\{T_{\theta N}\}=\{\theta_N\}^T\{T_\theta\}$

$$[C_N]=[\theta_N]^T[C][\theta_N]=\begin{bmatrix} C_{N11} & & & & \\ & C_{N22} & & 0 & \\ & & C_{N33} & & \\ & 0 & & C_{N44} & \\ & & & & C_{N55} \end{bmatrix}=$$

$$\begin{bmatrix} 2\tilde{\omega}_{n1}\zeta_{11} & & & & 0 \\ & 2\tilde{\omega}_{n2}\zeta_{22} & & & \\ & & 2\tilde{\omega}_{n3}\zeta_{33} & & \\ & & & 2\tilde{\omega}_{n4}\zeta_{44} & \\ 0 & & & & 2\tilde{\omega}_{n5}\zeta_{55} \end{bmatrix}$$

特征值矩阵$[\Omega_N^2]=[\theta_N]^T[K][\theta_N]=$

$$\begin{bmatrix} \tilde{\omega}_{n1}^2 & & & & \\ & \tilde{\omega}_{n2}^2 & & 0 & \\ & & \tilde{\omega}_{n3}^2 & & \\ & & & \tilde{\omega}_{n4}^2 & \\ & 0 & & & \tilde{\omega}_{n5}^2 \end{bmatrix}$$

3.3 求解

用四阶 Runge-Kntta 法对(1)求解, 可求出该齿轮传动系统的振动动态响应。

4 齿轮结构参数和误差对某动力装置主齿轮传动振动的影响计算结果

本文计算了如表 1 示的某型舰动力装置主齿轮传动的振动动态响应, 结果如下:

表 1　某型舰动力装置主齿轮传动结构参数

	一级		二级	
	小齿轮	大齿轮	小齿轮	大齿轮
模　数/mm	8.8		12.2	
压力角	20°		20°	
齿　数	29	92	33	156
齿　宽/mm	462(人字齿)		404(人字齿)	
螺旋角	25°		28°	
基圆半径/mm	132.3	380.4	214.2	506.9
材　质	17CrNiMo6		17CrNiMo6A	

4.1　螺旋角对齿轮振动的影响

舰用主齿轮传动一般采用斜齿轮传动。螺旋角越大，齿轮振动越小，因此，为减小振动，应尽可能采用大螺旋角的齿轮。

4.2　柔性扭力轴对齿轮振动的影响

图 3 为柔性扭力轴对 2 级小齿轮振动的影响曲线。从计算结果可以得如下结论：随着柔性扭力轴当量扭转刚度的增大，齿轮的振动加大。因此，在进行齿轮传动设计时，在保证足够的强度条件下，应尽可能选取刚度较小的柔性轴，以减少齿轮传动的振动。

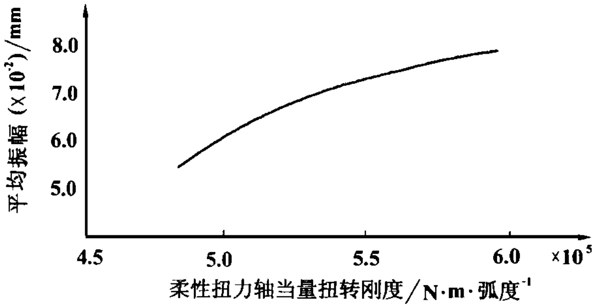

图 3　柔性轴刚度对二级小齿轮振动的影响

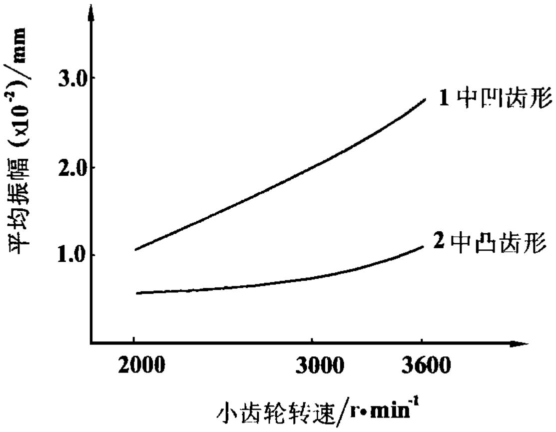

图 4　齿形误差对二级小齿轮振动的影响

4.3　齿形误差对齿轮振动的影响

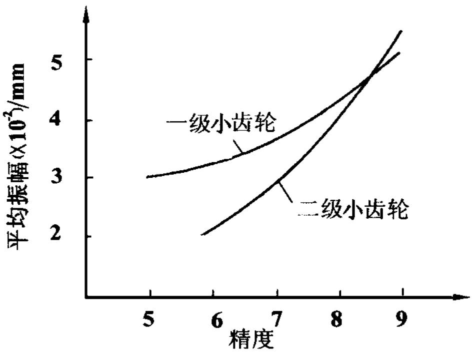

图 5　齿轮振动与设计精度的关系

如图 4 所示，齿形误差的幅值和形状对齿轮振动有很大影响，具有中凸齿形的齿轮振动特性要优于中凹齿形。因此在加工时节点附近应避免出现中凹齿形。

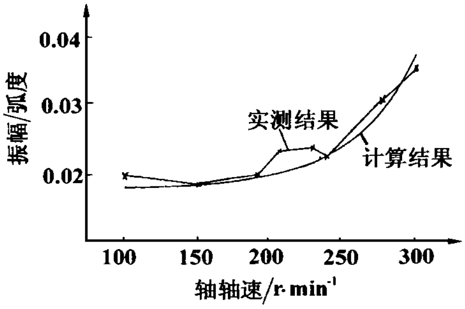

图 6　某型驱逐舰主齿轮传动振动实验结果与计算的比较

4.4　设计精度的影响

如图 5 示，设计精度对不同齿轮级的齿轮振动影响有显著差异，二级齿轮振动受设计精度影响更大。因此，在设计时尤其要合理选择二级齿轮的设计精度。

4.5　与实际结果的比较

图 6 为某驱逐舰主齿轮传动二级大齿轮振动实测结果与计算结果的比较，可以看出，两者基本吻合。

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(何静芳　编辑)

反切配风对大容量锅炉内流场特性影响的研究＝The Effect of an Reverse Tangential Air Distribution on the Flow Field Characteristics in a Large-sized Boiler Furnace［刊，汉］Zhou Qulan，Dou Wenyu，Zhou Yuegui，et al（Xi'an Jiaotong University）//Journal of Engineering for Thermal Energy & Power.－2000，15（2）.－116～118

The in-furnace flow-field characteristics of a large-sized boiler were studied by way of experimental measurements and numerical simulation. The results of the experimental measurements fully agree with those of numerical simulation. In addition，in both cases the same conclusions have been reached. They are：1. There exists at the furnace outlet of a large-sized boiler a speed excursion caused by a residual rotation；2. There is a wall attachment tendency in the actual tangential circle at the burner zone of the large-sized boiler；and 3. The reverse tangential air-distribution mode can effectively reduce the level of rotating momentum flow rate moment in the furnace，and markedly weaken the residual rotation at the furnace outlet. **Key words：** boiler，secondary-air reverse-tangential circle，model test，numerical simulation

齿轮结构参数和误差对某动力装置主齿轮传动振动的影响＝The effect of Gear Structural Parameters and Errors on the Main Gear Transmission Vibrations of a Marine Propulsion Plant［刊，汉］/Shi Huamin（Naval Engineering Academy）//Journal of Engineering for Thermal Energy & Power.－2000，15（2）.－119～121

Following the creation of a single-stage helical-gear transmission vibration model set up was a dynamics model for the main-gear transmission vibrations of a marine propulsion plant. A modal analysis method was employed to solve for the model. Analyzed and discussed was the effect of the structural parameters and errors on the main gear transmission vibrations. In addition，some pertinent conclusions were also obtained. **Key words：** gear transmission，vibration

同心反切燃烧方式的气固两相流动特性实验研究＝An Experimental Study of the Gas-solid Duel-phase Flow Characteristics of the Reverse Tangential Firing System（CFS-II）［刊，汉］/Wang Chungang，Zhu Qunyi，Li Zhengqi（Harbin Institute of Technology）//Journal of Engineering for Thermal Energy & Power，2000，15（2）.－122～124

Low-quality coal-fired boilers operating in a tangential firing mode often suffer from such problems as a deteriorating flame stabilization and water wall high-temperature corrosion. With respect to the above-cited issues an experimental study was conducted of the gas-solid dual-phase flow characteristics of the Tangential firing system（CFS-I）and the reverse tangenfial firing system（CFS-II）with the help of PDA（particle dynamic analyzer）system. The study results show that as compared to the CFS-I system the CFS-II system enjoys a better performance as regards the flame stabilization，low NOx emissions，heating-surface slagging and high-temperature corrosion. **Key words：** tangential firing system，reverse tangential firing system，gas-solid flow characteristics，particle dynamic analyzer

切圆燃烧流场中不同高宽比矩形喷嘴射流特性的试验研究＝Experimental Study of Jet Characteristics of a Rectangular Nozzle with Different Height-to-width Ratios in a Tangentially-fired Combustion Flow Field［刊，汉］/Zhang Ze，Wu Shaohua，Yao Zheng，et al（Harbin Institute of Technology），Li Min（Harbin Power Plant Equipment Group Corp.）//Journal of Engineering for Thermal Energy & Power.－2000，15（2）.－125～127

With the help of a hot wire anemometer a detailed experimental study was perfomed of the rigidity and turbulence characteristics of the jet flow of a primary-air rectangular nozzle with different height-to-width ratios in a tangentially-fired combustion flow field. Furthermore，the deflection and stable combustion mechanism of the rectangular nozzle jet flow under different height-to-width ratios is also analyzed. As a result，obtained was the optimum height-to-width ratio of the rectangular nozzle in the tangentially-fired combustion flow field. The study results may serve as helpful reference data for engineering design and general applications. **Key words：** tangentially-fired furnace，jet characteristics，height-to-width ratio，experimental study，hot wire anemometer